

Heavy quark production in pA collision with rcBK evolution

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Heavy Ion Collision

Aim of HIC exp.

- To create Quark-Gluon Plasma (QGP) in Lab.
- To study bulk properties of QGP

Observables

- EM probes ; leptons & photons
- Soft probes ; hadron distributions
- Hard probes ; jets, heavy flavor, Quarkonia



Toward comprehensive understanding

Heavy Quark System as Hard probe

 Scale hierarchy in quarkonia :

$$m \gg mv \gg mv^2$$

m : mass

$v \sim \alpha_s$: velocity

- Heavy quarks ($m \gg \Lambda_{\text{QCD}}$) are produced in perturbative process.
- HQs in Quarkonia moves slowly (mv) and their binding energy (mv^2) can be Λ_{QCD} scale.
- Quarkonium formation in QGP is sensitive to Debye screening.
- Modification of Open HQ due to Energy-loss and hadronization are also very important.

Strategy for HQ production in HIC

- pp : test of pQCD calculation
 - Quarkonium production mechanism remains as an open question.
- pA : nuclear pdf, multiple scattering
 - These effects will modify HQs and Quarkonium production
- AA : Hot medium effects
 - HQs Energy-loss
 - Quarkonium suppression and enhancement

Color Glass Condensate (CGC) describes multiple scattering and gluon distribution in Hadron. Typical saturation scale Q_s^2 reaches to a few GeV^2 at RHIC, LHC, and we expect that the saturation affects HQs and Quarkonium production.

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- Motivation
- Reviewing CGC formalism and x -evolution

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Color Glass Condensate (CGC)

see e.g. Iancu, Leonidov and McLerran, arXiv:hep-ph/0202270,
Iancu and Venugopalan, arXiv:hep-ph/0303204

McLerran-Venugopalan (MV) model

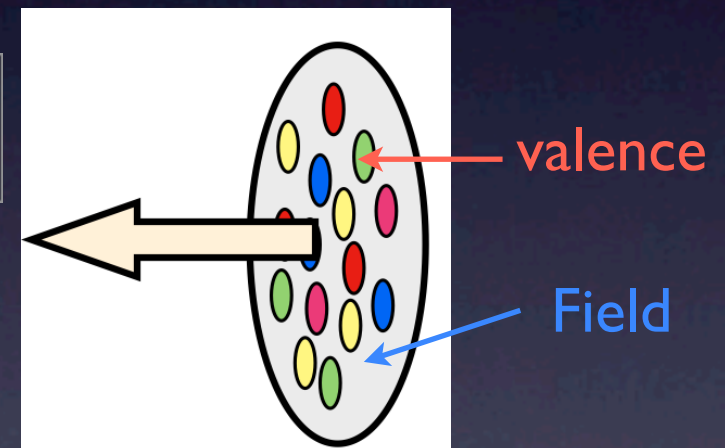
McLerran and Venugopalan, PRD49,50 (1994)

- **Large Bjorken- x** partons : random color sources (gaussian dist.)
- **Small- x** partons : classical fields produced from the sources



-multiple scattering
-no rapidity dependence

$A \gg I$



Quantum evolution of MV model : CGC

- Source dist. func. follows JIMWLK renormalization group eqn.

CGC provides us the framework to study the parton multiple scattering and quantum evolution effects.

General framework of CGC

Blaizot, Gelis, Venugopalan, PRA743 (2004)

Fujii, Gelis, Venugopalan, PRA780 (2006)

Consider the proton and nucleus colliding at the speed of light.

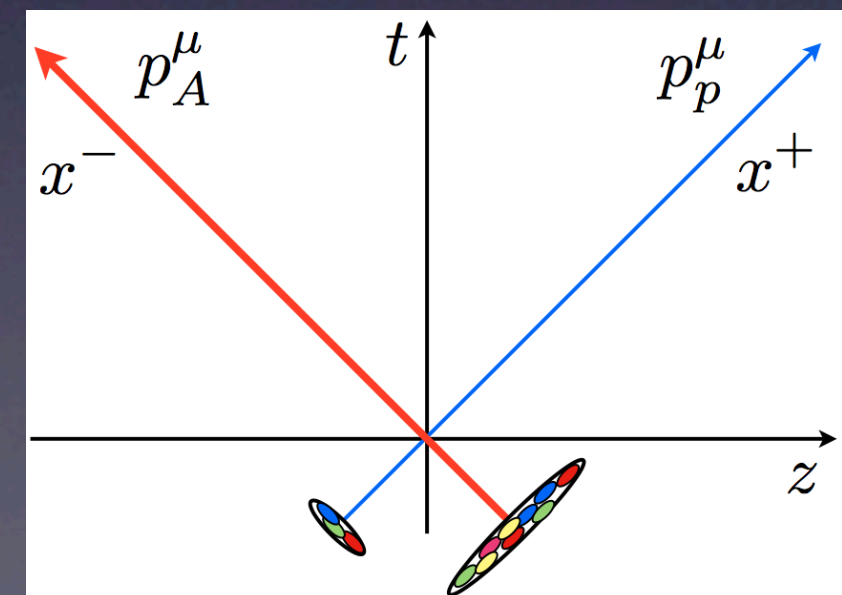
Color Current at **leading order** in the source

$$J_a^\mu = g\delta^{\mu+}\delta(x^-)\rho_{p,a}(\mathbf{x}_\perp) + g\delta^{\mu-}\delta(x^+)\rho_{A,a}(\mathbf{x}_\perp)$$

Yang-Mills Eqn ; background soft modes

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

HQ pair production amplitude is obtained by computing quark propagator in the background.



HQ pair production cross section

- A single QQbar pair production cross section at LO in gauge coupling.

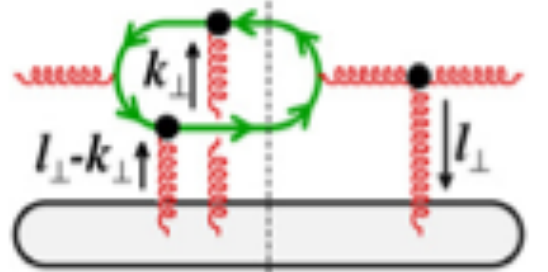
$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{q}_\perp d^2\mathbf{p}_\perp dy_q dy_p} = \frac{\alpha_s^2}{(2\pi)^4 C_F} \int_{\mathbf{k}_{2\perp}, \mathbf{k}_\perp} \underbrace{\Xi(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp}, \mathbf{k}_\perp)}_{\text{Hard matrix element}} \underbrace{\varphi_p^{g,g}(\mathbf{k}_{1\perp}) \phi_A^{q\bar{q},g}(\mathbf{k}_{2\perp}, \mathbf{k}_\perp)}_{\text{uGDs}}$$

Hard matrix element

uGDs

- uGD is expressed with dipole amplitude $S(\mathbf{k})$ in large- N_c

$$\phi_A^{q\bar{q},g}(\mathbf{k}_{2\perp}, \mathbf{k}_\perp) = \frac{\pi R_A^2 \mathbf{k}_{2\perp} N_c}{4\alpha_s} S(\mathbf{k}_{2\perp} - \mathbf{k}_\perp) S(\mathbf{k}_\perp)$$

$$\phi_A^{q\bar{q},g}(\mathbf{l}_\perp; \mathbf{k}_\perp) =$$


$$S(\mathbf{k}) = \text{F.T.} [1 - \mathcal{N}(r, Y)] = \text{F.T.} \left[\frac{1}{N_c} \text{tr} \langle \tilde{U}(\mathbf{r}_\perp) \tilde{U}(0) \rangle \right]$$

Quantum evolution in small-x region

- In large- N_c and large- A mean field approximation, JIMWLK eqn reduces non-linear **Balitsky-Kovchegov (BK) eqn**.
- We can obtain dipole amplitude by only solving BK eqn.

LO BK eqn

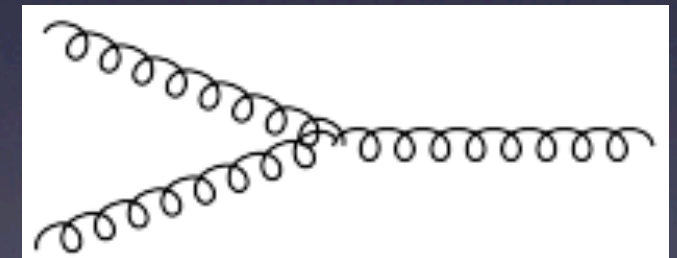
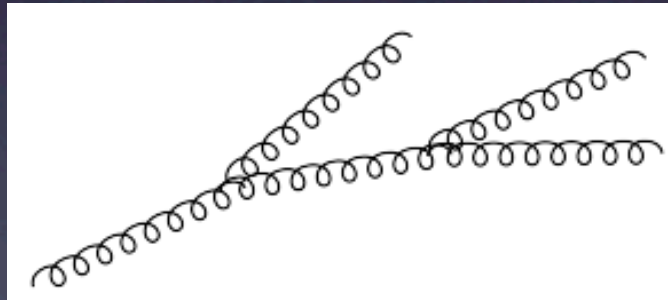
Balitsky, NPB463 (1996), Kovchegov, PRD60 (1999)

$$\frac{\partial \mathcal{N}(r, Y)}{\partial Y} = \int d\mathbf{r}_1 \mathcal{K}_{\text{LO}} \left[\mathcal{N}(r_1, Y) + \mathcal{N}(r_2, Y) - \mathcal{N}(r, Y) - \mathcal{N}(r_1, Y)\mathcal{N}(r_2, Y) \right]$$

gluon radiation

gluon fusion

$$Y = \ln(x_0/x), \quad r = r_1 + r_2$$



- **Gluon recombination** effect becomes more important in forward rapidity region, which corresponds to smaller x .

rcBK evolution

- Running coupling effect as LO correction is included, and evolution kernel becomes scale dependent one.

Gardi et al., NPA784 (2007), Balitsky, PRD75 (2007),
Kovchegov and Weigert, NPA784 (2007)

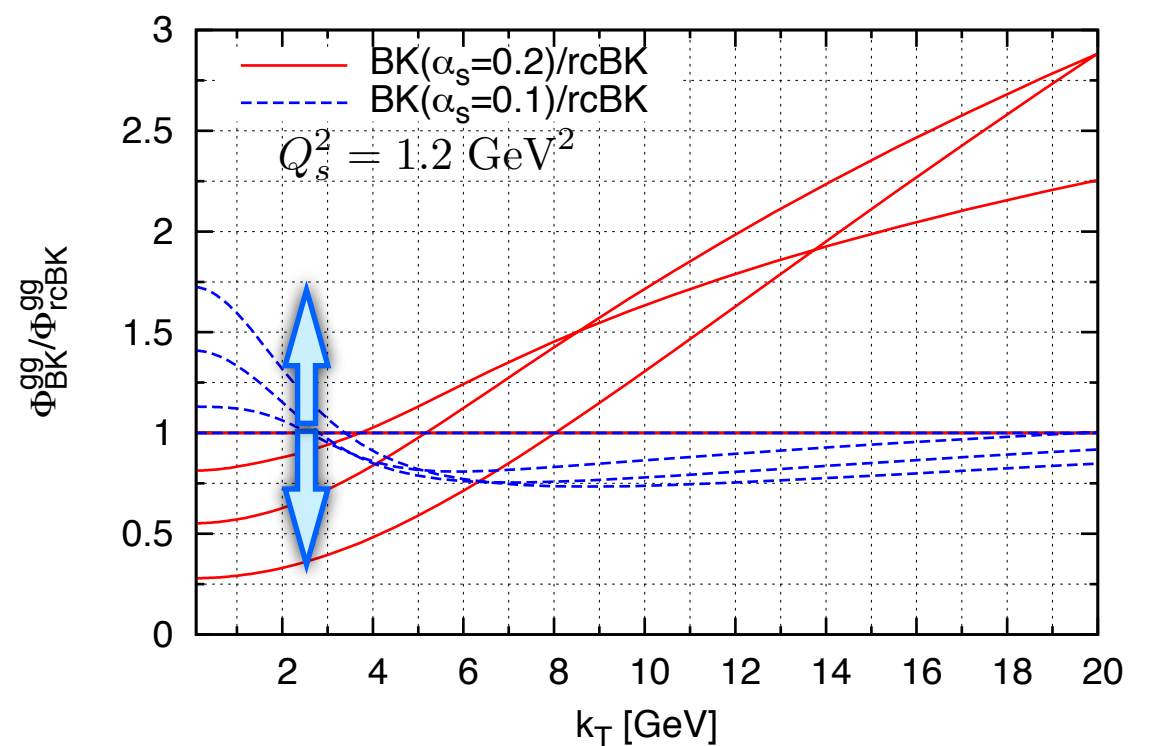
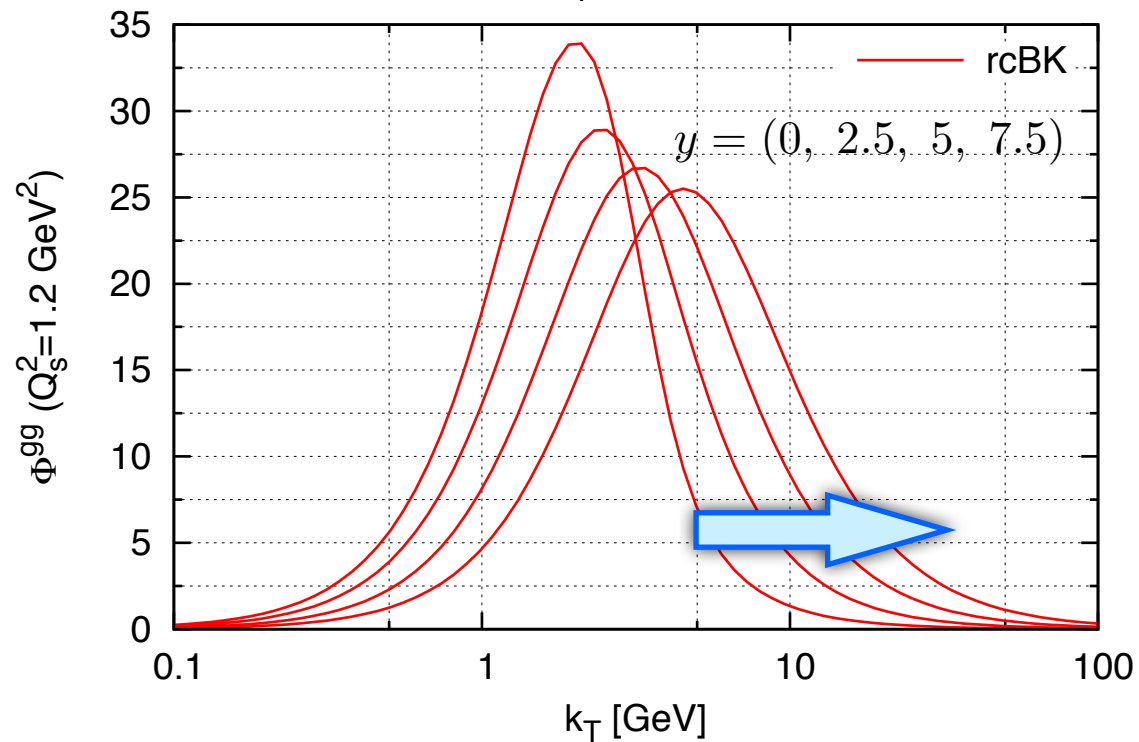
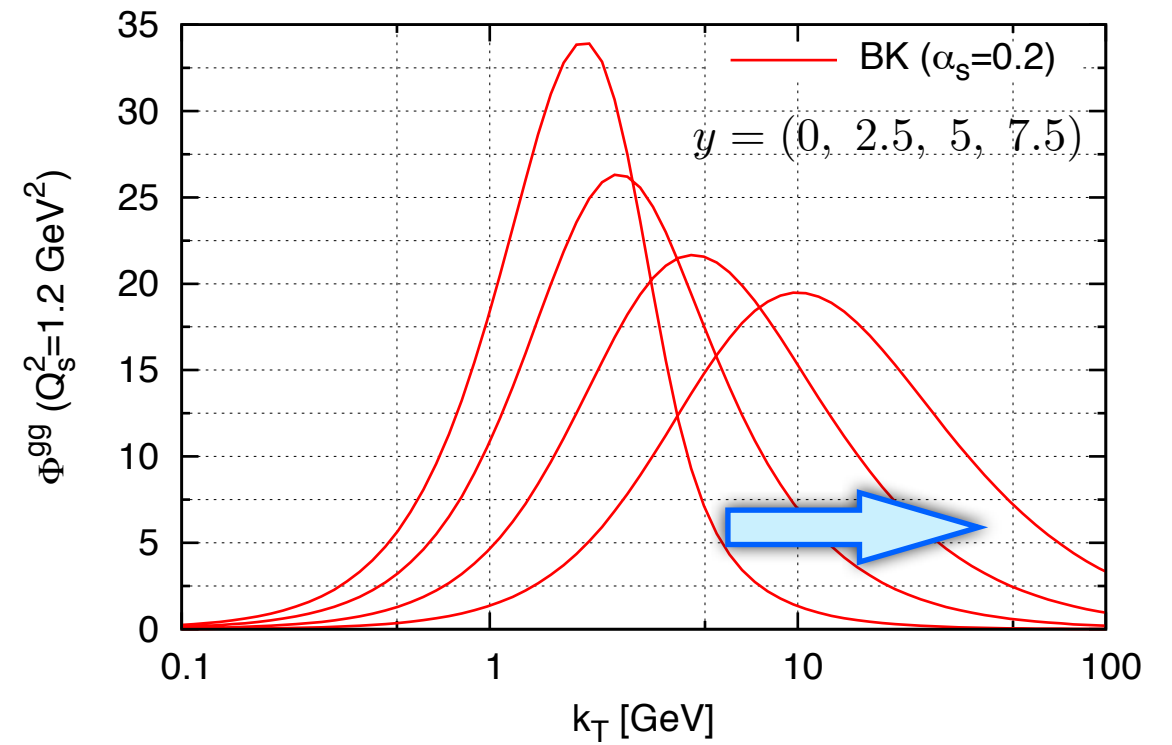
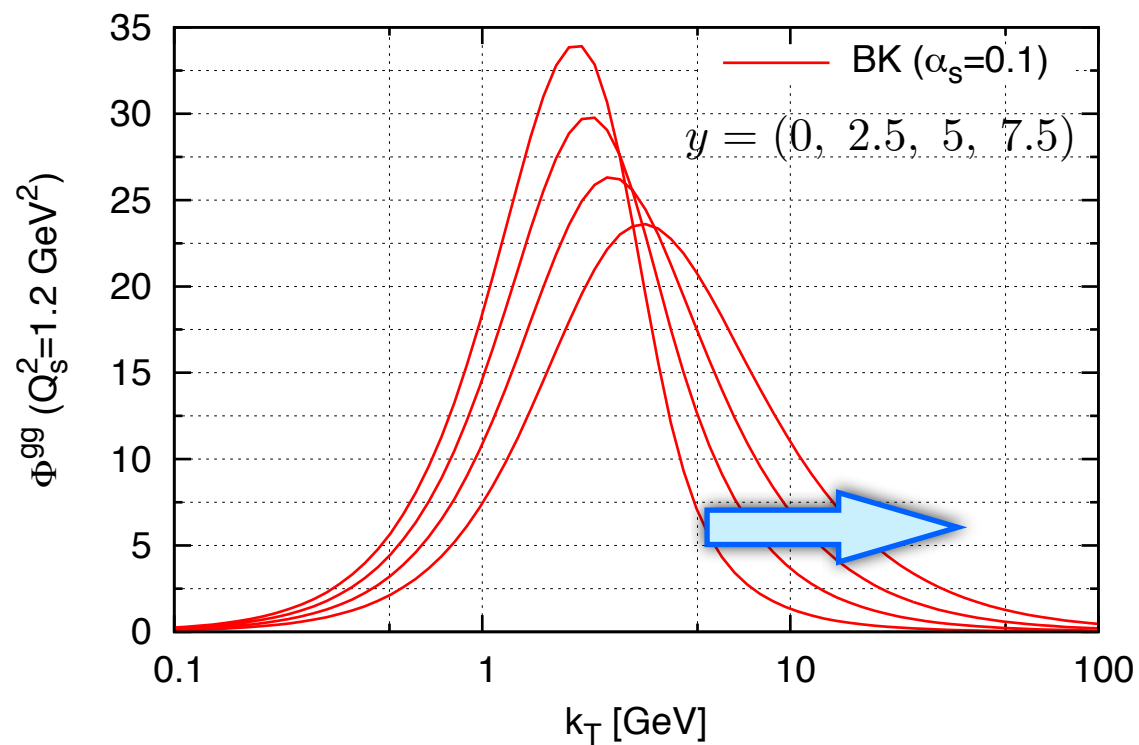
$$\frac{\partial \mathcal{N}(r, Y)}{\partial Y} = \int d\mathbf{r}_1 \mathcal{K}_{\text{run}} [\mathcal{N}(r_1, Y) + \mathcal{N}(r_2, Y) - \mathcal{N}(r, Y) - \mathcal{N}(r_1, Y)\mathcal{N}(r_2, Y)]$$

$$\mathcal{K}_{\text{LO}} = \frac{N_c \alpha_s}{2\pi^2} \frac{r^2}{r_1^2 r_2^2} \quad \text{Fixed coupling}$$
$$\rightarrow \mathcal{K}_{\text{run}} = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[\frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right] \quad \text{Balitsky's prescription}$$

1-loop running
coupling :

$$\alpha_s(r^2) = \frac{1}{\beta_2 \ln \left(\frac{4C^2}{r^2 \Lambda_{\text{QCD}}^2} \right)}$$

rcBK solutions ; uGDs



Evolution speed ; $BK(\alpha_s=0.1) \sim rcBK$

CGC phenomenology

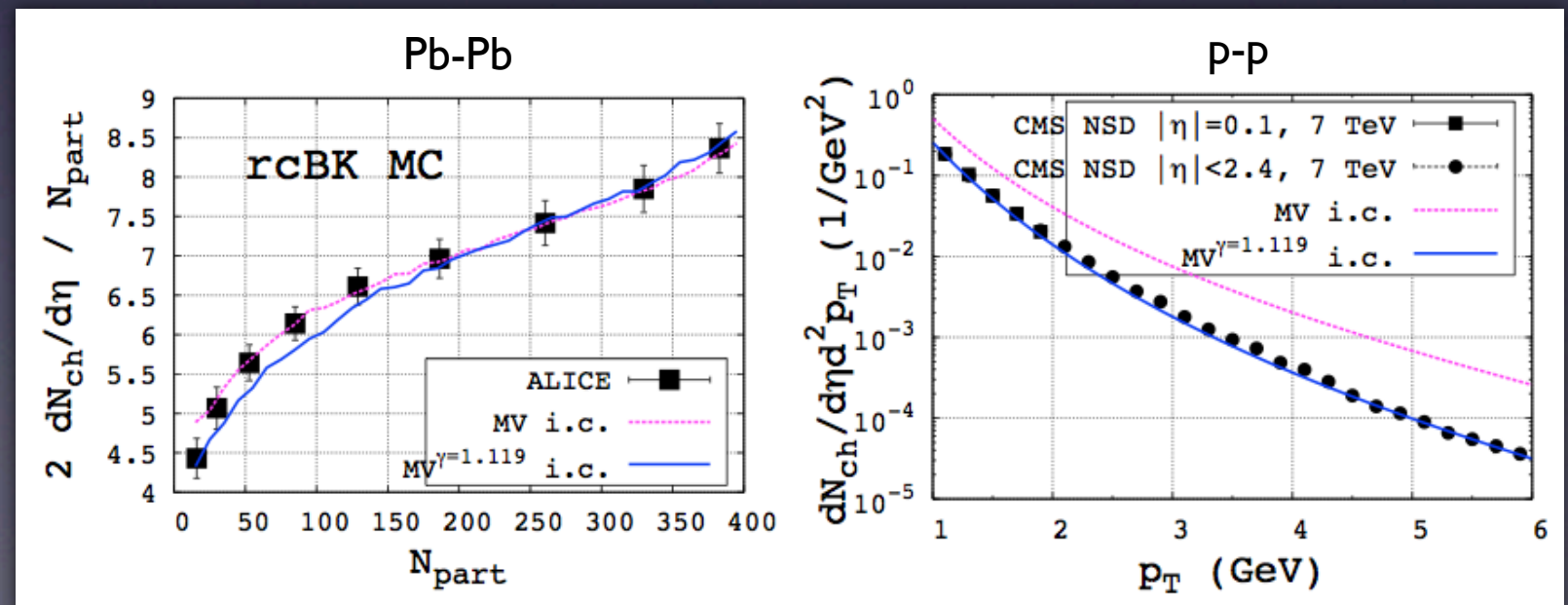
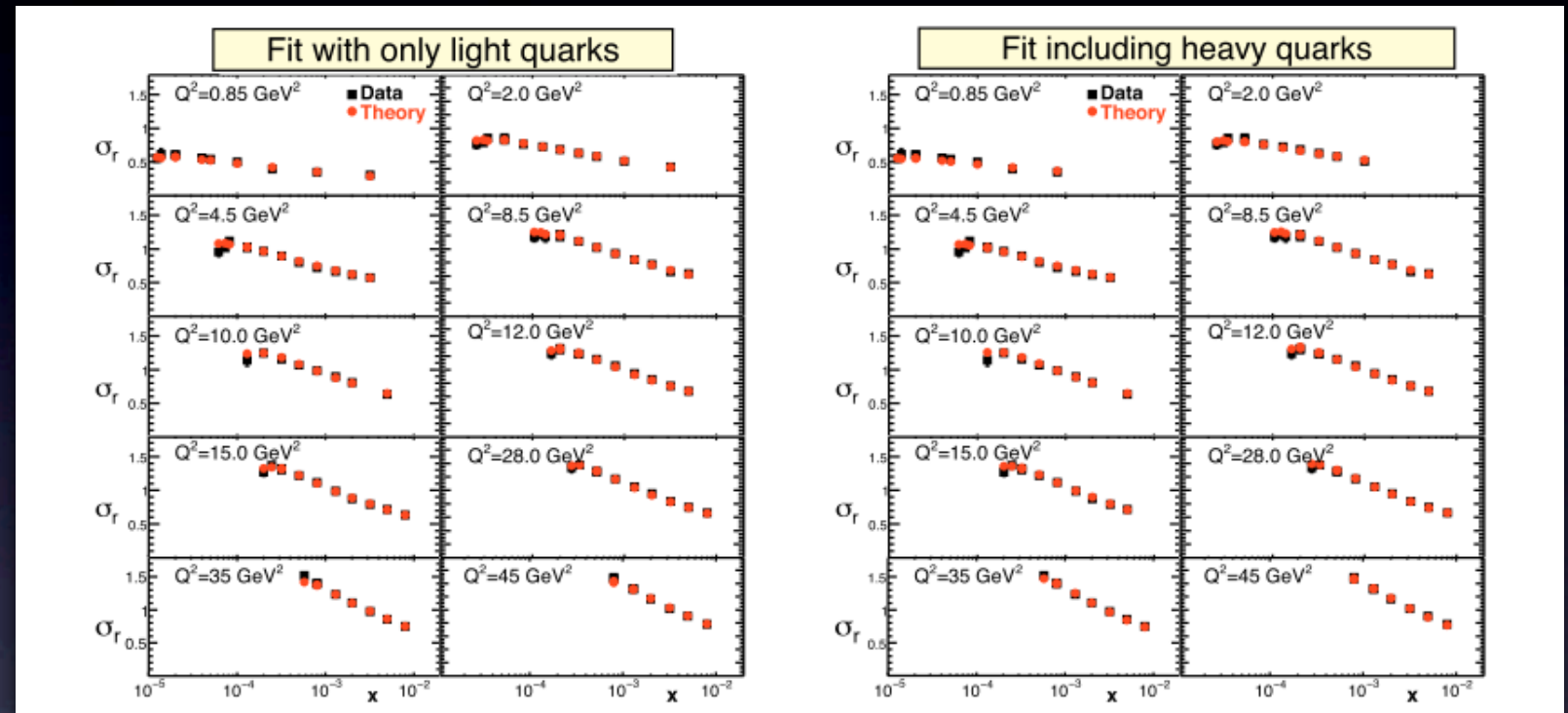
Applications of rcBK eqn have been successful in describing some exp. data.

DIS @ HERA

AAMQS, EPJC71(2011)

dN/dy @ LHC

Albacete and Dumitru,
arXiv:hep-ph/10115161



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Setup

- MV model for Initial condition of dipole.
McLerran and Venugopalan, PLB424 (1998)

$$\mathcal{N}^{\text{MV}}(r, x = x_0 = 0.01) = 1 - \exp \left[-\frac{r^2 Q_{s0}^2}{4} \ln \left(\frac{1}{r\Lambda} + e \right) \right]$$

- Initial saturation scale at $x_0=0.01$

$$Q_{s0}^p{}^2 = 0.2 \text{ GeV}^2, \quad Q_{s0}^A{}^2 = A^{1/3} Q_{s0}^p{}^2 = 1.2 \text{ GeV}^2$$

~6 for Au / Pb

- Here we only discuss the Nuclear Modification Factor ;

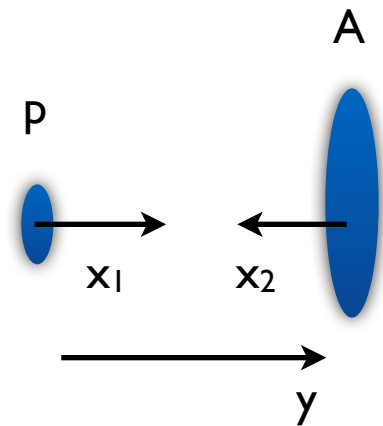
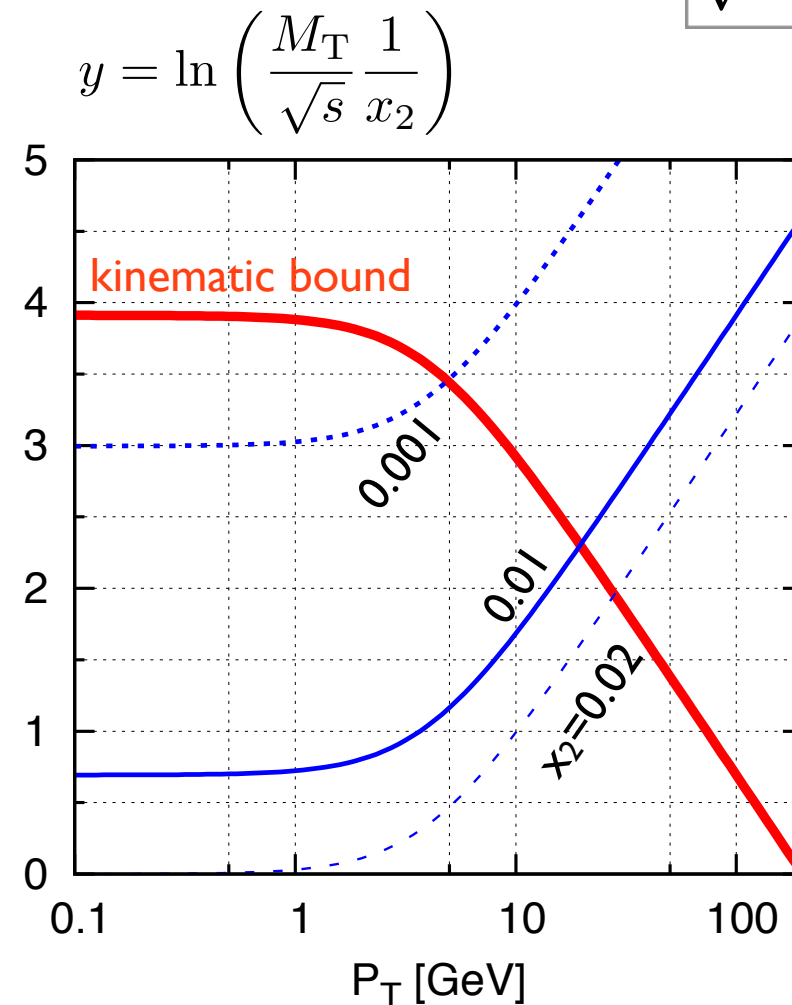
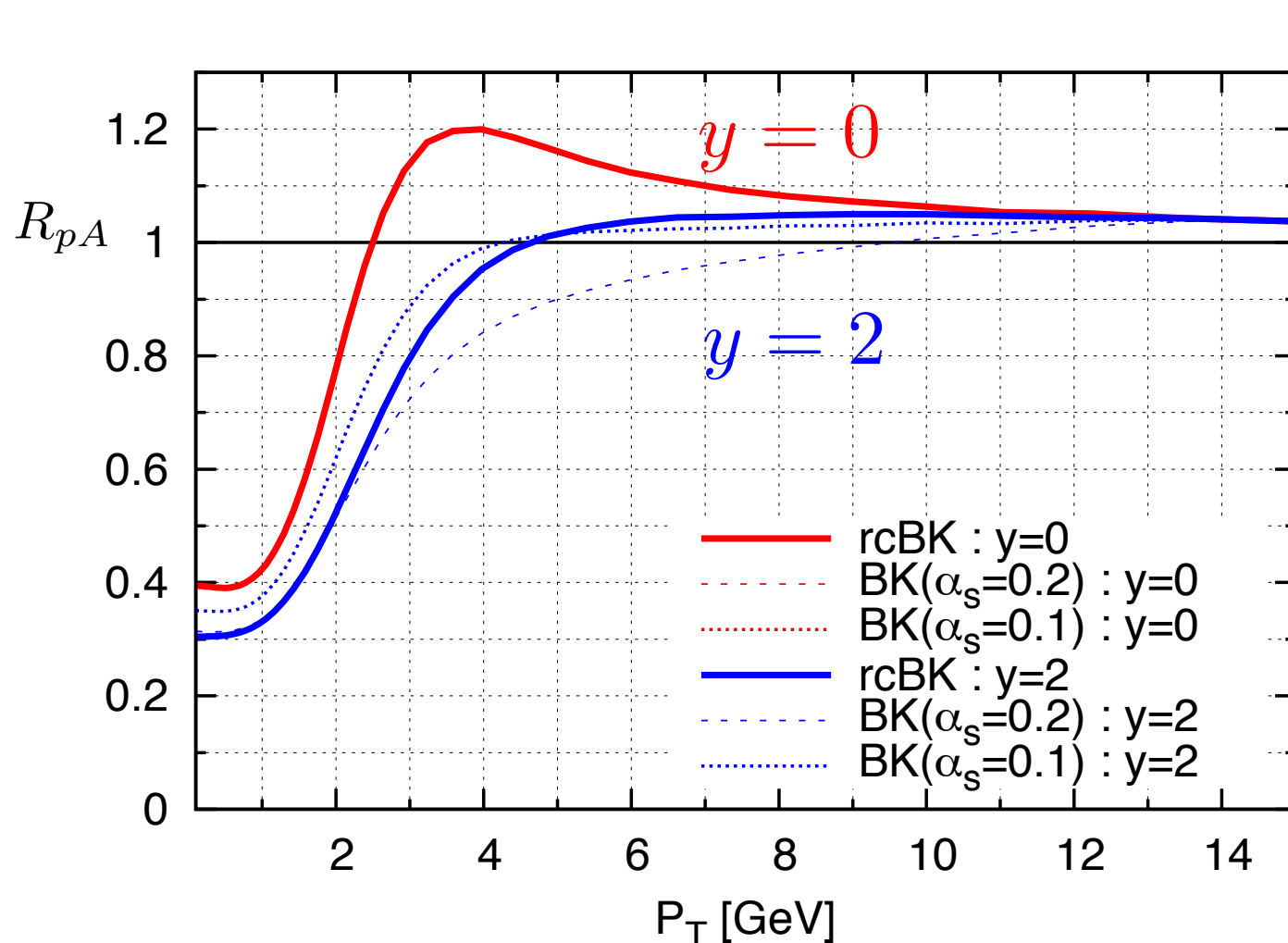
$$R_{pA} = \frac{d\sigma_{pA}}{N_{\text{coll}} d\sigma_{pp}} = \frac{d\sigma_{pA}}{6 \times d\sigma_{pp}}$$

to study the running coupling effect by computing
LO cross section + LO BK or rcBK eqns.

Charm-pair : vs P_T @RHIC

Charm mass $m=1.5$ GeV, Invariant mass $M=4$ GeV

$$\sqrt{s} = 200 \text{ GeV}$$

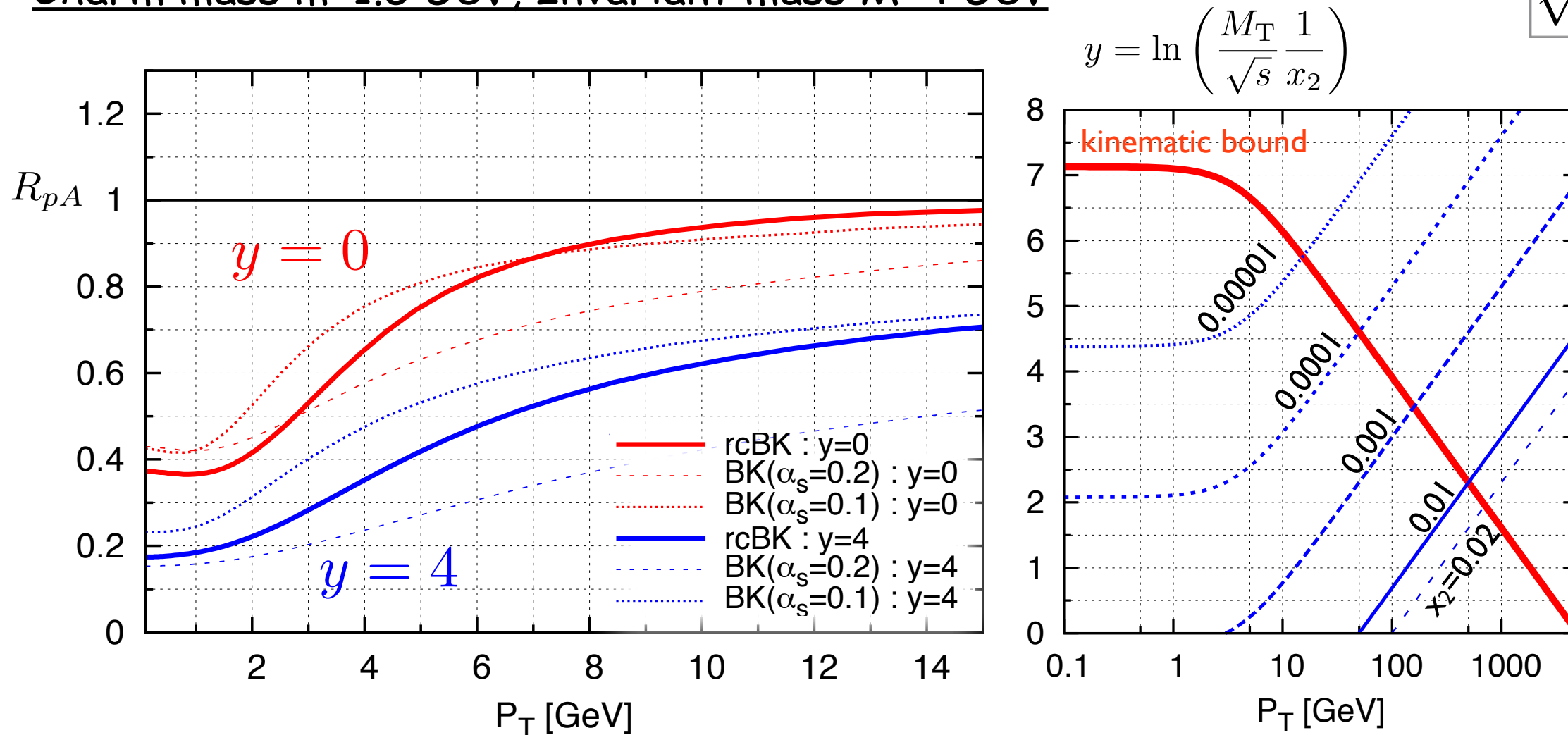


- $y=0$; Cronin peak, fixed by initial model at $x_0=0.01$
- $y=2$; Evolution effects are seen.
- rcBK vs BK eqns ; some quantitative difference

Charm-pair : vs P_T @LHC

Charm mass $m=1.5$ GeV, Invariant mass $M=4$ GeV

$$\sqrt{s} = 5\text{TeV}$$

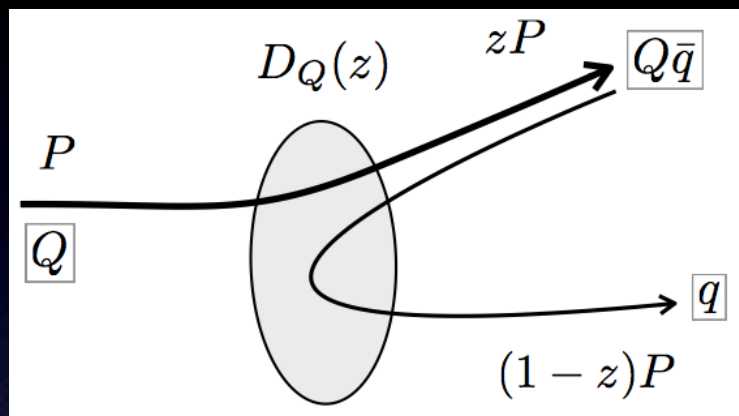


- $y=0$; x_2 is already very small.
- $y=0, 4$; strong suppression due to x -evolution
- rcBK vs BK ; difference becomes larger than at RHIC
- In large- P_T region, rcBK result approaches BK one with $\alpha_s=0.1$.

Fragmentation function

🌀 Open Heavy Flavor : **Peterson's fragmentation function.**

Peterson et al. PRD27 (1983)



$$D_Q(z) = \frac{N}{z[1 - (1/z) - \epsilon_Q/(1-z)]^2} \quad \epsilon_Q \sim \frac{m_q^2}{m_Q^2}$$

🌀 Quarkonium : We suppose that the bound states are produced via soft color interaction (**Color Evaporation Model**) both in the pp and pA collision.

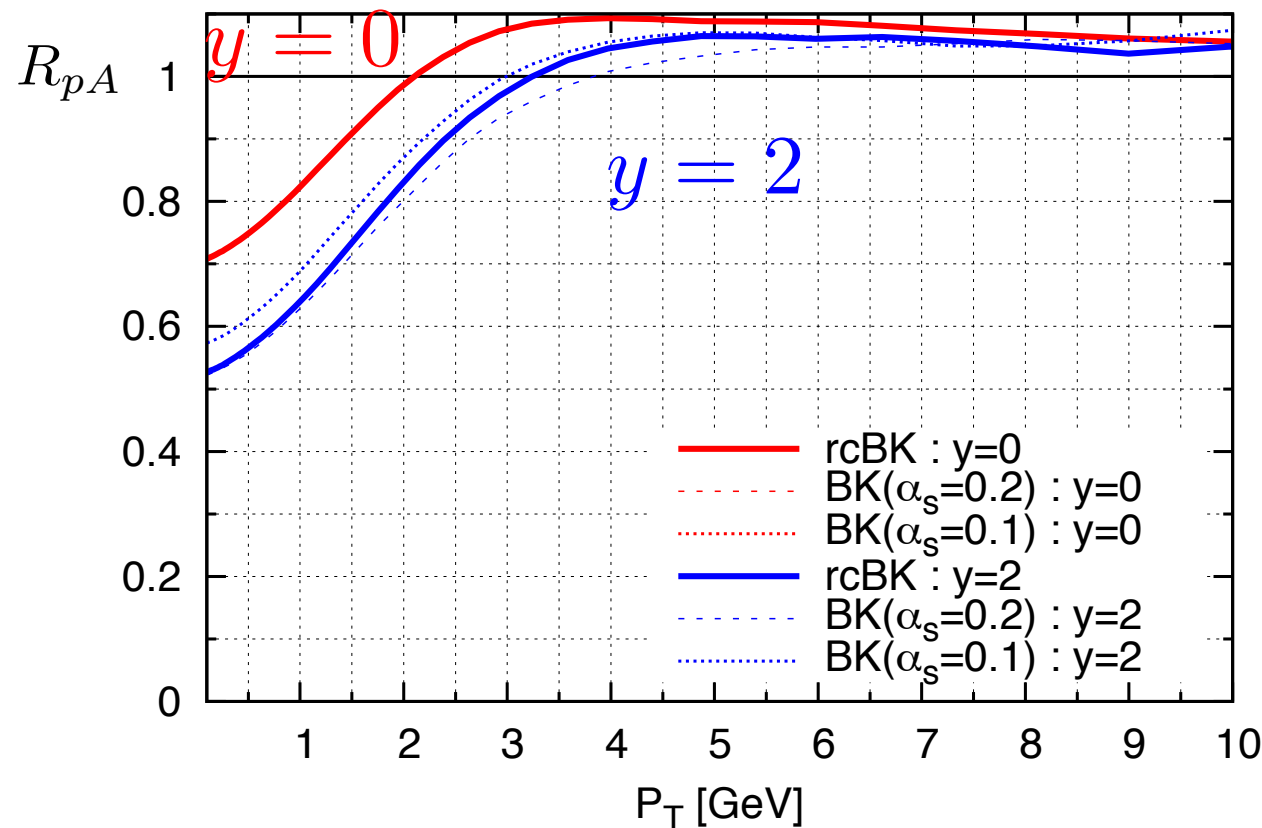
$$d\sigma_{(Q\bar{Q})} = F_{(Q\bar{Q})} \int_{2m_Q}^{2m_{Q\bar{q}}} dM \frac{d\sigma}{dM}$$

Spin polarization → Future study

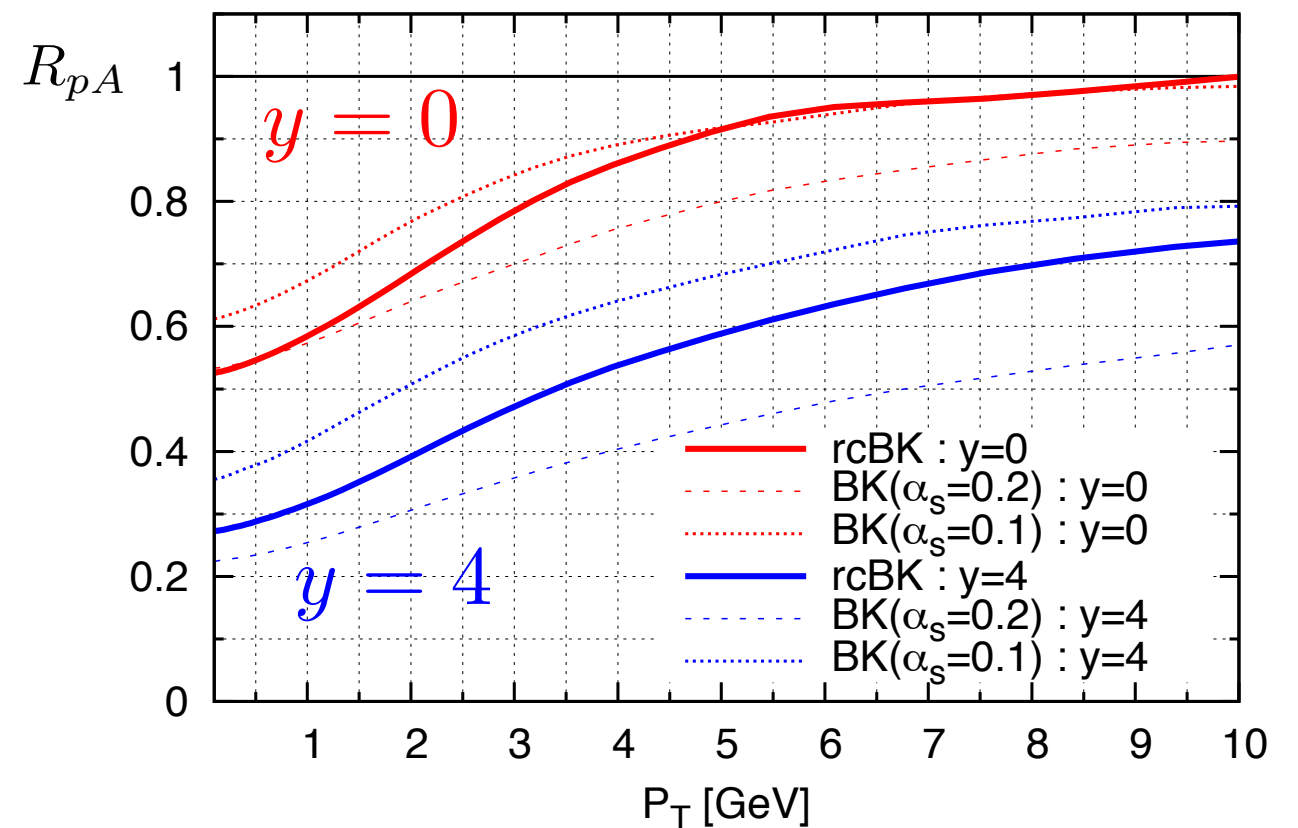
D-meson : vs P_T

Charm mass $m=1.5$ GeV

$\sqrt{s} = 200\text{GeV}$

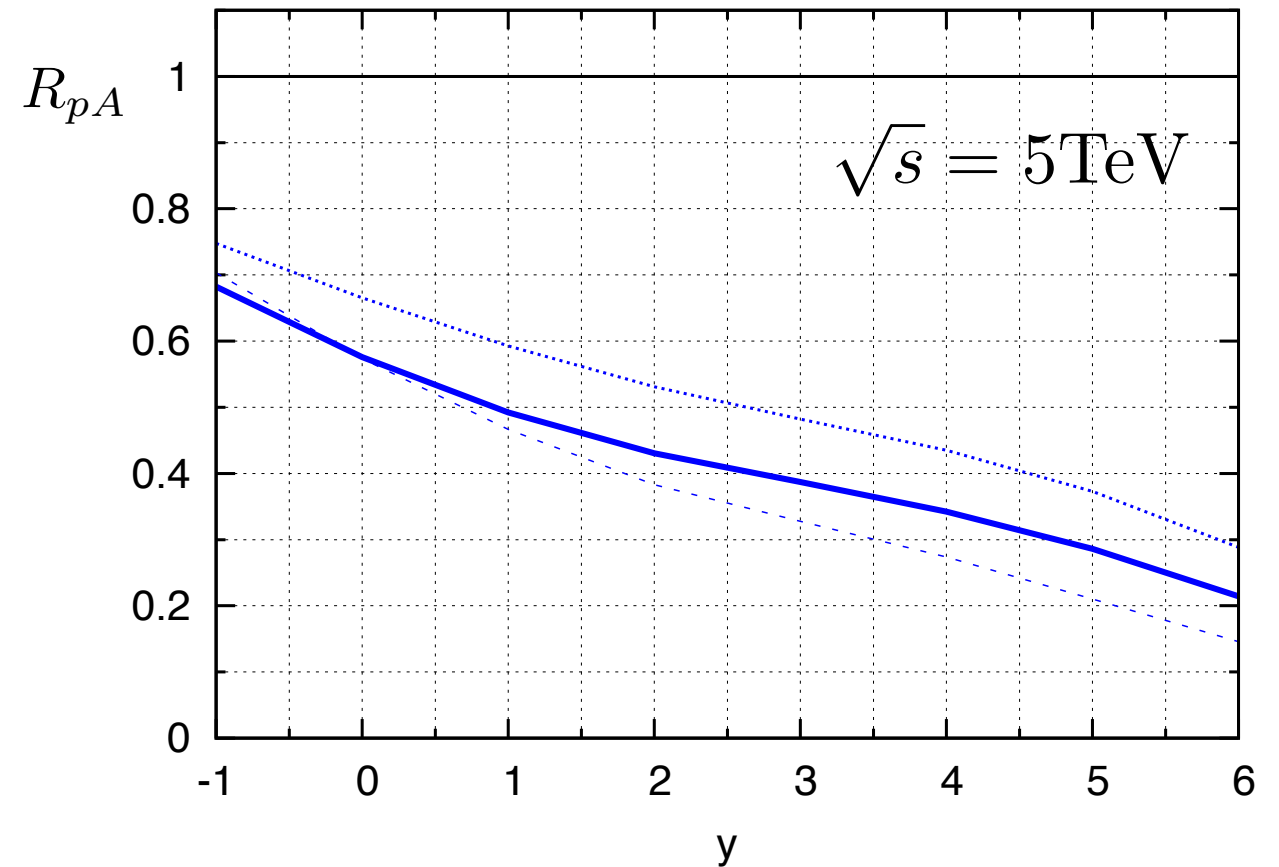
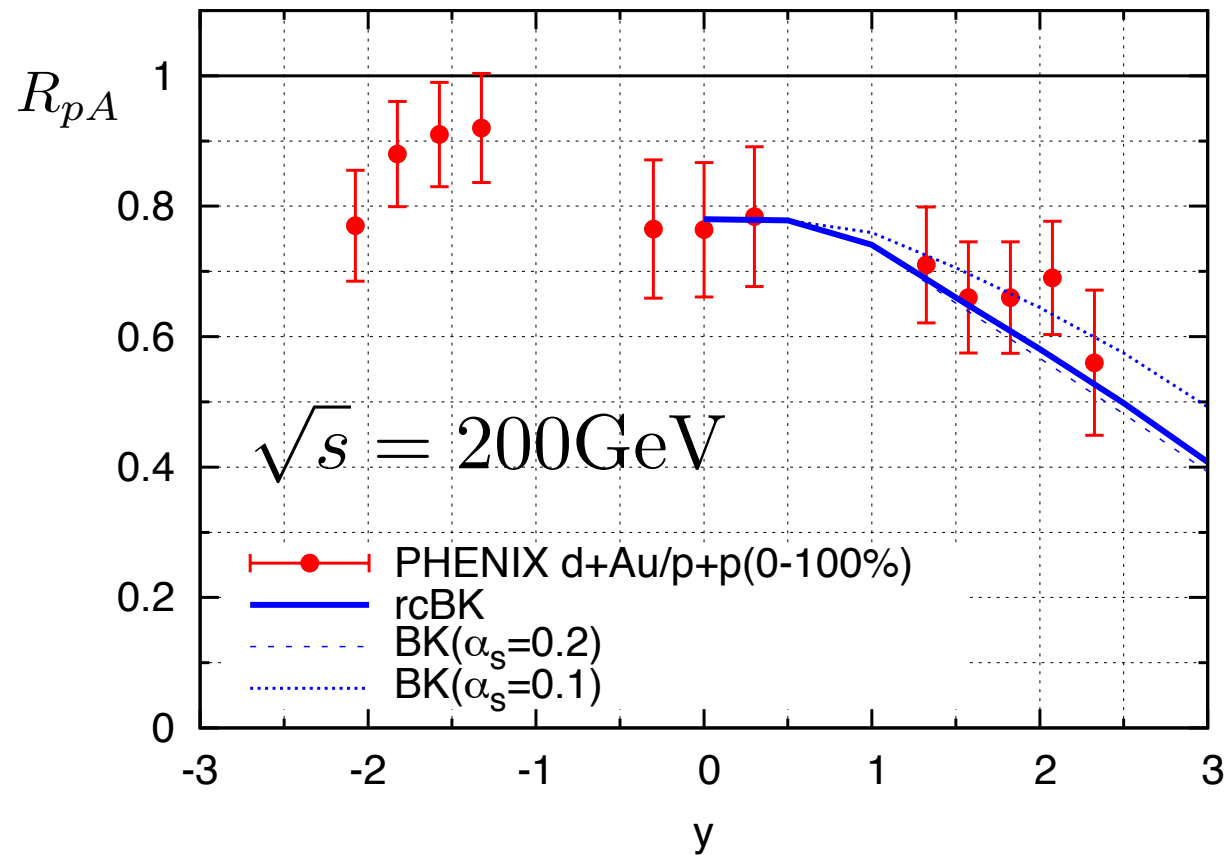


$\sqrt{s} = 5\text{TeV}$



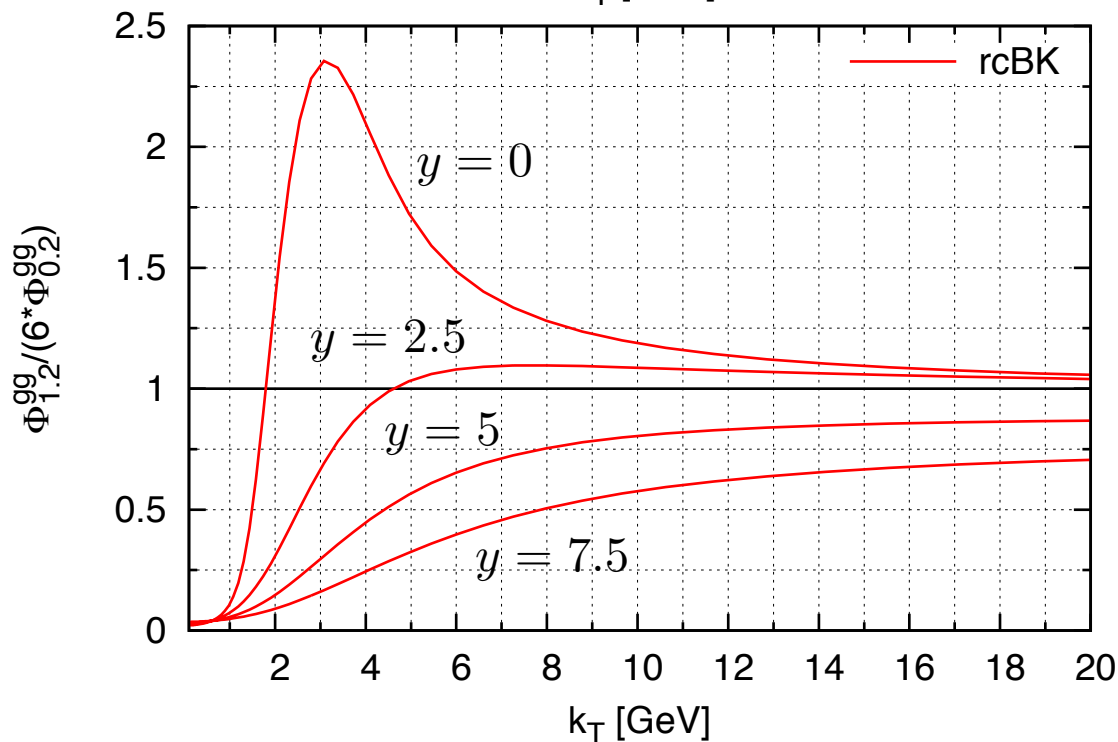
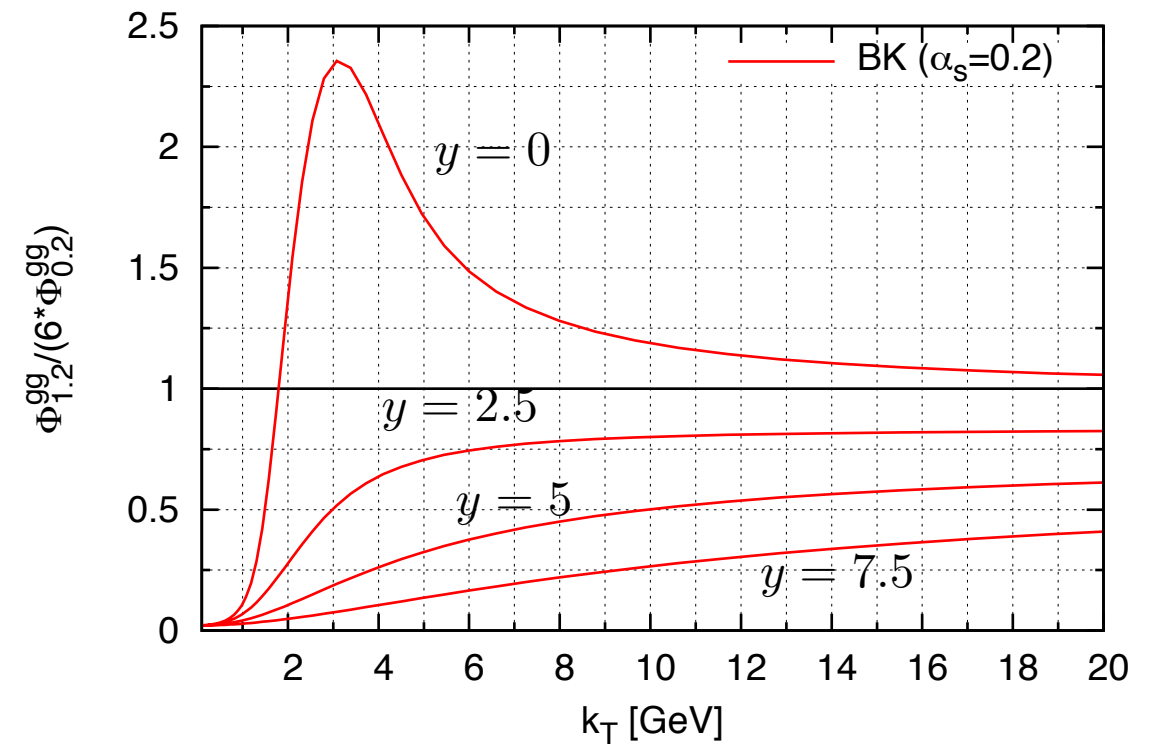
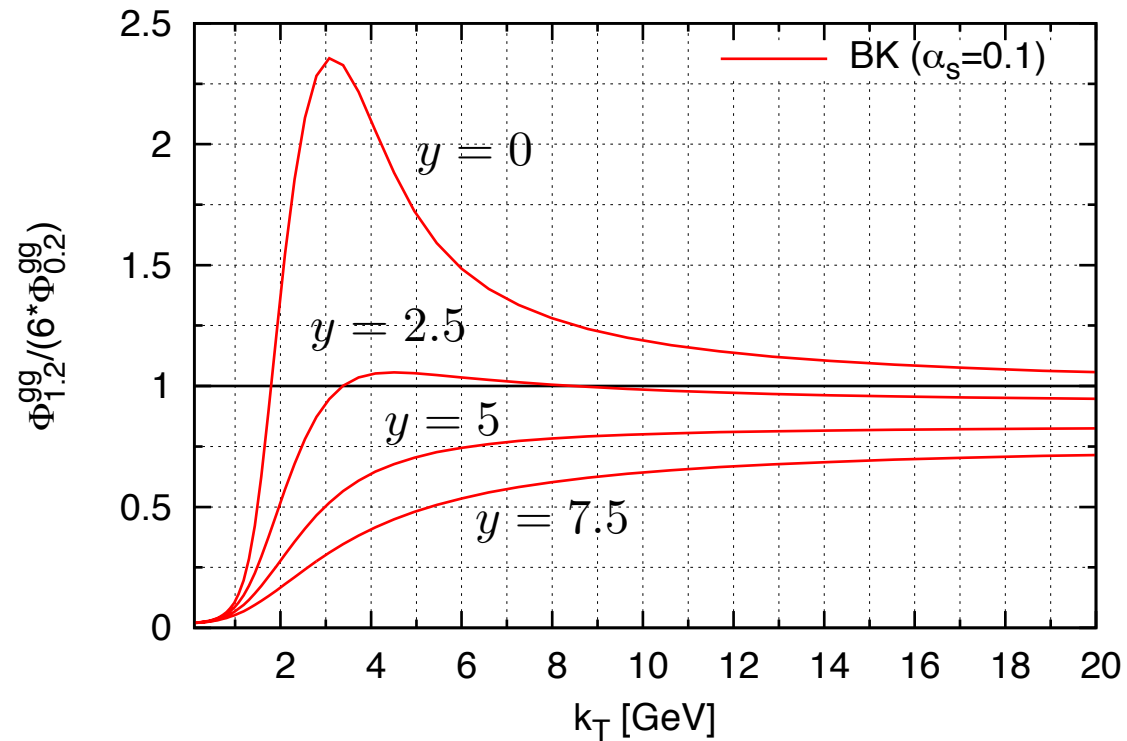
- $y=0$ at RHIC energy; Cronin peak is small
- Qualitative results of Open Heavy flavor production are similar to results of HQ pair production.

J/ψ : vs y (Integrating over P_T)



- Good agreement with exp. data “at RHIC”
- Other parameters set \rightarrow Future study
- rcBK result is close to BK result with $\alpha_s=0.2$

From uGDs



$$\frac{\Phi^{gg}(Q_s^2 = 1.2 \text{ GeV}^2)}{6 \times \Phi^{gg}(Q_s^2 = 0.2 \text{ GeV}^2)}$$

- P_T dependence of R_{pA} cannot be explained only from a ratio of uGDs.
→ Future study

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Summary

- CGC provides the framework to study the multiple scattering and saturation effects on HQs and Quarkonium production in pA collision.
- We found that the saturation effects manifest even in the HQ and Quarkonium production in the forward rapidity region at the RHIC energy as well as in wider rapidity region at the LHC energy.
- rcBK and LO BK eqns result in quantitatively different P_T dependences of R_{pA} of HQs and Quarkonium.

Outlook

We will elaborate the model toward unified description of nuclear effects from DIS to pA with rcBK eqn.